SELF-SYNCHRONIZED CONVERTER FOR FAST SYNCHRONIZATION BETWEEN LOW VOLTAGE MICROGRID AND INVERTER CONNECTION

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To my beloved parents and wife

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ABSTRACT

In this research, a fast-synchronization between single-phase microgrid and inverter in low voltage, which is based on virtual synchronous converter (VSCon) technique is been developed. This technique does not require any phase locked loop (PLL) circuit as an external control structure for the synchronization of the inverter. As known, PLL is a common technique in order to synchronize the amplitude, phase-angle and frequency between a microgrid and an inverter in distributed generation network. Previous studies show that, the disadvantage of PLLs is where the non-linear characteristic on the signal process will result the inverter control to be non-linear. Therefore, it is difficult and lengthy process to tune the PLL gains to reach suitable performance in order to synchronize the voltage, phase-angle and frequency between microgrid and inverter. As a result, a VSCon is been developed in which it is a self-synchronized inverter which is based on synchronous generator mathematical model. This controller acts like as synchronous generator operating system in inverter control loop in order to achieve fast voltage, phase and frequency synchronization between inverter-microgrid connection. This technique has been modeled, simulated and tested in Matlab/Simulink software. It is by using a single-phase AC source input system connecting with several load variations during simulation period. This VSCon has been placed in inverter control loop to generate a pulse width modulation (PWM) signal that responds to the grid information for to synchronizing the inverter output voltage with the grid voltage. A single source input at 120V, 50Hz frequency and 240V, 50Hz frequency are used in order to see the self-synchronization response between a microgrid and an inverter. Furthermore, it also been tested when the grid frequency has been changed from the rated frequency at 50Hz to 51Hz and the result shows that, VSCon takes nearly 1-cycle to synchronize to this new frequency value. The grid phase angle test also has been conducted. For this test, the voltage grid which has 10^0 phase delay has been created in the input voltage source at microgrid side. As a result, the VSCon is also able to achieve self-synchronization with this new source

input phase delay in just within 1.5 cycles or 30ms after the inverter has been connected to the microgrid. From all the results that have been collected, this technique can be an improved model for inverter to have synchronization between inverter and microgrid which is not require a PLL circuitry model in order to maximize the power transfer from the inverter to the microgrid when it been applied to the distributed generation network.

ABSTRAK

Dalam kajian ini, penyegerakan cepat antara micro-grid dan fasa tunggal penyongsang arus terus (AT) kepada arus ulang (AU) alik bagi voltan peringkat rendah, yang berasaskan maya penukar segerak teknik (VSCon) telah dibangunkan. Teknik ini tidak memerlukan mana-mana litar gelungan kunci fasa (PLL) sebagai struktur kawalan penyongsang AT-AU sebagai fungsi penyegerakan antara micro-grid dan penyonsang didalam penjanaan pembahagian litar elektrik. Seperti yang diketahui, PLL adalah kaedah biasa untuk menyelaraskan amplitud, frekuensi dan fasa-sudut antara microgrid voltan dan penyongsang. Kajian sebelum ni menunjukkan, kelemahan PLL adalah di mana ciri-ciri bukan linear keatas proses isyarat yang akan menyebabkan kawalan penyongsang sebagai tidak linear. Oleh itu, VSCon telah dibangunkan di mana, pemodelan matematik penyegerakan cepat diasaskan berdasarkan struktur penjana segerak. Kawalan yang direka adalah berdasarkan penjana segerak yang akan digunakan dalam kawalan penyongsang AT-AU untuk menghasilkan penyegerakan cepat dengan sambutan frekuensi dan voltan yang tepat pada sambungan penyongsang-microgrid. Teknik ini telah dimodelkan disimulasikan dan diuji didalam perisian Matlab / Simulink. Ia dengan menggunakan sistem satu fasa sumber input kepada penyongsang AT-AU tunggal yang akan dihubungkan dengan beberapa beban variasi didalam jaringan microgrid. VSCon yang direka akan dilaksanakan dalam kawalan penyongsang untuk menjana modulasi lebar denyut (PWM) isyarat yang mana maklumat-maklumat di grid bertindak balas untuk menyelaraskan voltan keluaran penyongsang dengan voltan grid tanpa menggunakan PLL dengan cepat. Ujikaji pertama, ia diuji apabila sumber input tunggal pada 120V, dengan frekensi 50Hz dan sumber input 240V, 50Hz digunakan untuk melihat tindak balas pada penyegerakan diri antara microgrid dan inverter. Selain itu pula, ia juga telah diuji apabila perubahan kekerapan grid dari frekuensi semasa iaitu 50Hz kepada 51Hz yang mana hasilnya menunjukkan bahawa, VSCon hanya mengambil masa hampir satu kitaran lengkap untuk menyegerakkan kepada nilai kekerapan baru ini yang diperlukan oleh grid. Untuk ujian sudut fasa grid juga dijalankan dimana grid voltan yang mempunyai 10 sudut kelewatan fasa telah diwujudkan atas sumber voltan input di sebelah microgrid. Hasilnya, VSCon dapat membuat penyegerakan pantas dengan

kelewatan baru ini, dalam masa satu setengah kitaran atau dalam masa 30ms selepas penyongsang AT-AU disambungkan kepada microgrid itu. Dari semua keputusan yang telah dihasilkan, teknik kawalan ini boleh menjadi model yang lebih baik kepada penyongsang AT-AU untuk dapat memberi penyegerakan pantas antara penyongsang AT-AU tanpa model litar PLL untuk memaksimumkan pemindahan kuasa antara penyongsang dan microgrid itu sekiranya perlu didalam talian pembahagian penjanaan.

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LIST OF SYMBOLS AND ABBREVIATIONS

D	Friction Coefficient
i_f	Field current
J	Virtual rotor inertia
I_L	Load current
I_C	Inverter current
M	Inertia
M_f	Mutual field inductance
P	Real Power
P_{in}	Input mechanical power
P_{out}	Output electrical power
Q	Reactive Power
S	Second
T_e	Electrical torque
T_m	Mechanical torque
V_g	Grid voltage
X_s	Synchronous reactance
$\varphi_{coupling}$	Voltage angle at coupling point
$\dot{\theta}$	Virtual angular speed of rotor
$\ddot{\theta}$	Virtual angular acceleration of rotor
θ_g	Grid voltage phase
AC	Alternate Current

CORDIC	Coordinate Rotation Digital Computer
CSI	Current Source Inverter
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
EPLL	Enhanced Phase Locked Loop
FLL	Frequency Locked Loop
GI	Generalize Integrator
GSC	Grid Side Converter
MHDC	Multi-harmonic Decoupling Cell
MW	Megawatt
PCC	Point of Common Coupling
PCM	Power Control Mode
PI	Proportional Integral
PID	Proportional Integral Differential
PLL	Phase Locked Loop
PMS	Power Management System
PWM	Pulse Width Modulation
RES	Renewable Energy System
RMS	Root Mean Square
SOGI-PLL	Second Order Generalized Integral PLL
SRF-PLL	Synchronous Reference Frame PLL
THD	Total Harmonic Distortion
VCM	Voltage Control Mode
VCO	Voltage Controlled Oscillator
VSI	Voltage Source Inverter
VSCon	Virtual Synchronous Converter

CHAPTER 1

INTRODUCTION

1.1 Introduction

Distributed generations (DGs) have attracted the researchers around the world due to several advantages such as reduce the emission of greenhouse gases, increasing the reliability of the system and alleviating the pressure on power transmission system. According to [1], the distributed energy resources based on microgrid system are a good solution to transfer the electric power from DGs to the existing electrical grid and at the meantime to supply the electric power to the local loads in order to ensure reliable power supply if the primary power supply fails to deliver the power to the load. Most of the distributed sources need power converter mechanisms in order to control the power flows to the microgrid. When the DGs share the power, the power system becomes noteworthy for preserving and it improve the stability of the power system [2]-[3]. The important task during power sharing is to maintain an accurate synchronization condition between both sources.

Commonly, two parts of power processing strategies are required in order to send the power from DGs to the microgrid. First, the harvested energies from the distributed sources are converted into electrical power by using dc power converters. For example, the non-conventional energy sources such as PV offers direct current/voltage to be stored into rechargeable battery bank, but it needs a dc converter to maintain the voltage level at the dc-link battery. Then this battery connects to the existing ac low voltage microgrid network through an efficient power processing devices [4] such as the inverter. Due to these advantages, DG-microgrid is catching more room to be researched in order to export more power to the grid from the DG. In this point of view, smart and intelligent coupling between microgrid and DGs become significant issue for transferring the power with good and fast synchronization mechanism. As usual, current-source inverter (CSI) or voltage source inverter (VSI) is used as a power processing converter to supply the power from the DG to the microgrid. As compared to CSI, VSI is an inverter that has ability to control the inverter output voltage and it does need external reference to keep the inverter voltage to synchronize with the grid voltage [5]. After it has been synchronized, other control systems such as frequency droop and voltage droop can be applied to perform autonomous power flow to the microgrid [6]. Before the power can be transferred, both inverter and microgrid require synchronization stage in terms of voltage, frequency and phase angle to be the same in both side. Then the inverter can feed the power to the grid; even the microgrid voltage changes it frequency, phase, and amplitude [7]. Figure 1.1 shows the typical synchronization and power control structure for microgrid-connected inverter.

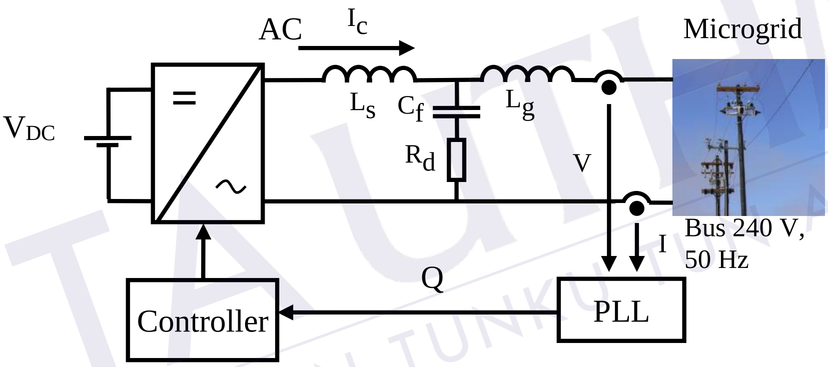

Figure 1.1: Typical control structures for low voltage microgrid-connected inverter

The synchronization unit, which is the digital PLL block shown in Figure 1.1 needs to provide frequency, amplitude, and phase information from the microgrid voltage in order to generate a reference phase signal for the inverter control [8] for synchronization and power delivery. Many power control approaches focuses with the aim of transferring power into the microgrids from DGs such as [9][10][11][12] with voltage source control, power angle control, torque angle control and current control. Before the power can be transferred, PLL is commonly used technique for synchronization. Conversely, to adopt the synchronization using PLL, all parameters that are the phase angle and frequency need to be included for inverter outer and inner loop controllers before it can be synchronized. This slow process on microgrid parameters will affect the overall control performances and increase the time of synchronization.

As known, the synchronous generator does not required PLL to transfer the power to the electrical network. It is when, the synchronous generator has reached a mature technology for electrical power transfer which is not required PLL and this had triggered a concept of self-synchronization for DGs inverter application [13]. It is where the output voltage profile depends only on the generator physical construction and input mechanical power. In such cases, frequency and amplitude of voltage are depended on angular speed of prime mover and field excitation of rotor coil of generator. For replacing the PLL operation, several mathematical models and algorithms that can behave as a generator inside the inverter control can be implemented. This technique is called synchronverter that has been proposed in [13][14]. Based on this concept, several improvements have been made especially on the frequency and phase tracking of the inverter-microgrid with low voltage connection. Therefore, this improved version of synchronverter can work in grid-connected or stand-alone mode since it has ability to control the voltage and the frequency of the inverter output. Moreover, by maintaining the proper control on the voltage and the frequency on inverter, it will able to share real power and reactive power into the grid at the same time.

In this research, synchronous generator model has been used to develop a virtual synchronous converter (VSCon) with an improved version of synchronverter in order to achieve the capability of self-synchronizing with a low voltage microgrid system without the aid of a dedicated PLL synchronization unit. The VSCon synchronization between inverter and low voltage microgrid has been attained in 20ms in case when 10° phase shift happens to the input voltage source. However, it has widened the frequency bandwidth of the system and it is able to reduce the time needed for synchronization, and improves the accuracy of synchronization. It also improves the performance of the system but also reduces the complexity of the overall synchronization system mechanism.

1.2 Problem statement

The phase locked loops (PLLs) have a slow synchronization unit, where it could inherently affect control performance and degrade system stability [14]. In addition, a complex synchronization unit is often computationally intensive, which adds significant burden to the controller. Therefore, the synchronization needs to be done quickly and accurately in order to maintain the synchronization [14]. It makes the design of the controller and the synchronization units is very challenging because the synchronization unit is often not fast enough with acceptable accuracy. Moreover, in distributed generation system, PLL circuitry increase computational burden for controller unit for synchronization as well as normal PLL does not effect on phase changes due to line impedance affect. In case of frequency, changing in the grid source given in paper [14], which used 20V and 50Hz system has been studied and changing in 0.1Hz frequency in the microgrid, it takes approximately 0.45s, which is nearly 22 cycles to stabilize the rated frequency.

1.3 Objectives

The objectives of this research are as follows:

1. To review various topologies of the synchronization between the inverter and low voltage microgrid in DG connection system.
2. To develop the synchronous generator mathematical model for inverter control strategy for fast synchronization between the inverter and the low voltage microgrid without using PLL structure.
3. To simulate and test the proposed synchronization technique using Matlab/Simulink in several load conditions.

1.4 Scope of project

The scope of this research project are given as below:

1. The proposed synchronized controller model is limited to accept a voltage level between 120V and 240V at 50 Hz frequency in single-phase connection.
2. To limit the testing, the Matlab/Simulink simulation models to 24V, 120V and 240V inverter-grid voltage at different load conditions.
3. The VSCon inverter model also has been limited with full-bridge rectifier as a non-linear load system condition in single-phase inverter.

4. This self-synchronization model will also been simulated in different phase-angle and frequency changes along the simulation time.

1.5 Thesis Organization

This research work structured into five chapters. Details and specific explanation to every section will be discussed below:

Chapter 1: This is the Introduction of the research project. It consists of background of research, the research problem, research objective and scope of project.

Chapter 2: Literature review will look at the previous researches within the scope especially on the PLL applications. It looks at factors contributing to synchronization between inverter and microgrid connection with several structures of PLL in the grid application. At the end of this chapter it will be organized and tabulated from all the paper review for summaried based on parameters affecting performance of a synchronization unit.

Chapter 3: This chapter will discuss the methods that will be adopted in self-synchronization between low voltage microgrid and inverter. The flow charts of phase synchronization and frequency synchronization have been discussed including complete model of VSCon.

Chapter 4: In chapter 4, the VSCon model will be simulated in Matlab/Simulink in various load conditions at different voltage levels of 24V, 120V and 240V at 50 Hz frequency. The different significant changes in simulation results will be discussed while changing grid voltage phase-angle and frequency also will be discussed. The comparison between low voltage microgrid and inverter synchronization using PLL and using VSCon also will be illustrated in this chapter.

Chapter 5: The last chapter in the research summaries the entire research work conducted and the conclusion. The future research were given for possible actions to be taken.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to distributed generation

Nowadays, distributed energy resources (DERs) [15][16] have attracted to extra consideration in various technological advances since petroleum based energy production contaminates large scale of greenhouse gases emission as well as high maintenance cost [17][18]. This capacity is expected to reach 2,080 MW by 2020, contributing to 7.8% of total installed capacity in Peninsular Malaysia and Sabah [19].

Distributed generation (DG) is not a new concept by itself. A number of patrons utilize electricity from home-side electricity generation plant by their own facilities. Nowadays, researchers emphasize more efforts to small resources of electricity spreading all over the world. With the advantages of new technology, it becomes one of the most competitive positions in the business of energy. It is developed with driving contribution not only on green energy but also on utilizing fewer resources. Many countries minimize the transmission and distribution cost by introducing locally producing energy and locally consuming energy rules strategy of distributed generation [20].

Moreover, distributed generators are not only limited to synchronous generators, induction generators, reciprocating engines, micro turbines, combustion turbines or gas turbines but also fuel cells, solar photovoltaic and wind turbine. DG is meant to shift the structure of the utility system from a centralized, radial system to energy source connected on the distribution level.

The benefits of applying DG in existing distribution system network have both of economic and technical point of positive although benefits ultimately counted in terms of money over the technical advantages. The benefits in two groups of technical and economic [21][22][23] as shown in Table 2.1.

Table 2.1: Benefits of distributed generation

Technical side	Economic side
Reduces line losses	Defers investment for facilities upgrades
Voltage profile improvement	Reduces operation and maintenance cost
Reduces emissions of pollutants	Enhances productivity
Increases overall energy efficiency	Reduces health care cost by improving environment
Enhances system reliability and security	Increases overall efficiency by reducing fuel costs
Improves power quality	Reduces reserve requirements and the associated costs
Relieves transmission and distribution congestion	Lowers operating costs due to peak shaving

The major drawback of renewable energy systems (RES) is the primary investment, which is comparatively larger than conventional system. For example, a gas turbine system may be built for USD500.00 per kilowatt, while for a wind turbine the investment is quite high as much as USD 1000.00 per kilowatt. On the other hand, RESs have special particulars of site and the unpredictability of the power generated. The availability of renewable energy like sun, wind or water mostly determines the feasibility of a RES and this may raise environmental issues. The unpredictability of RES also means of higher cost for balancing the electricity microgrid and maintain reserve capacity for example in the event that the fluctuation of wind speed and direction. In this case of abnormalities and system control technology, most of the DERs need power electronics interfaces to be connected to the microgrid [4].

2.2 Structure of microgrids

The consortium for electric reliability technology solutions (CERTS) first proposed the definition of microgrids: CERTS microgrid concept believes an aggregation of loads and micro-sources operating as a single system providing both power and heat. The majority of the micro-sources must be power electronic based to provide the required flexibility to guarantee operation as a single collective system. This control flexibility permits the CERTS microgrid to present itself to the bulk power system as

References

1. Marinelli, M. Sossan, F. Costanzo, GT and Bindner, HW. Testing of a Predictive Control Strategy for Balancing Renewable Sources in a Microgrid. *IEEE Transactions on Sustainable Energy*. 2014;5(4):1426–33.
2. Lee, C-T. Chu, C-C and Cheng, P-T. A New Droop Control Method for the Autonomous Operation of Distributed Energy Resource Interface Converters. *IEEE Transactions on Power Electronics*. 2013;28(4):1980–93.
3. Blaabjerg, F. Teodorescu, R. Liserre, M and Timbus, AV. Overview of Control and Grid Synchronization for Distributed Power Generation Systems. *IEEE Transactions on Industrial Electronics*. 2006;53(5):1398–409.
4. Vasquez, JC. Guerrero, JM. Gregorio, E. Rodriguez, P. Teodorescu, R and Blaabjerg, F. Adaptive droop control applied to distributed generation inverters connected to the grid. In: 2008 IEEE International Symposium on Industrial Electronics. IEEE; 2008. p. 2420–5.
5. Rocabert, J. Luna, A. Blaabjerg, F and Rodríguez, P. Control of Power Converters in AC Microgrids. *IEEE Transactions on Power Electronics*. 2012;27(11):4734–49.
6. Sultani, JF. Gow, JA and Tez, E. Modelling, Design and Implementation of D-Q Control in Single-Phase Grid-Connected Inverters for Photovoltaic Systems Used in Domestic Dwellings. 2013;1–272.
7. Shinnaka, S. A Novel Fast-Tracking D-Estimation Method for Single-Phase Signals. *IEEE Transactions on Power Electronics*. 2011;26(4):1081–8.
8. Amin, MR and Rajib Baran Roy. Design of microcontroller based Thyristor Controlled three-phase static volt-ampere reactive compensator. In: 2014 International Conference on Informatics, Electronics & Vision (ICIEV). IEEE; 2014. p. 1–6.
9. Hadjidemetriou, L. Kyriakides, E. Yang, Y and Blaabjerg, F. A synchronization method for single-phase grid-tied inverters. *IEEE Transactions on Power Electronics*. 2016;31(3):2139–49.
10. Chung, SK. A phase tracking system for three phase utility interface inverters. *IEEE Transactions on Power Electronics*. 2000;15(3):431–8.
11. Silva, SM. Lopes, BM. Filho, BJC. Campana, RP and Bosventura, WC. Performance evaluation of PLL algorithms for single-phase grid-connected

systems. *Conference Record of the 2004 IEEE Industry Applications Conference, 2004 39th IAS Annual Meeting*. 2004;4(1):2259–63.

12. Mastromauro, RA. Liserre, M and Dell'Aquila, A. Control Issues in Single-Stage Photovoltaic Systems: MPPT, Current and Voltage Control. *IEEE Transactions on Industrial Informatics*. 2012;8(2):241–54.
13. Zhong, QC and Weiss, G. Synchronverters: Inverters that mimic synchronous generators. *IEEE Transactions on Industrial Electronics*. 2011;58(4):1259–67.
14. Zhong, QC. Nguyen, P-LP. Ma, Z and Sheng, W. Self-synchronised Synchronverters: Inverters without a Dedicated Synchronisation Unit. *IEEE Transactions on Power Electronics*. 2014;29(c):1–1.
15. Ackermann, T. Andersson, G and Söder, L. Distributed generation: a definition. *Electric Power Systems Research*. 2001;57(3):195–204.
16. Amin, MR. Roy, RB and Hasan, MM. Modeling and Optimization of Decentralized Microgrid System for St. Martin's Island in Bangladesh. *International Journal of Energy, Information and Communications*. 2014;5(5):1–12.
17. Amin, M. R and Roy, RB. Determination of Electric Vehicle Power Consumption for Assorted Pavement Gradient Using Matlab/Simulink. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014;12(9):6602–11.
18. Ruhul Amin, M and Roy, RB. Design and simulation of wireless stationary charging system for hybrid electric vehicle using inductive power pad in parking garage. *The 8th International Conference on Software, Knowledge, Information Management and Applications (SKIMA 2014)*. 2014;(March):1–5.
19. Economic Planning Unit. Eleventh Malaysia Plan: 2016-2020, Anchoring Growth on People. *Rancangan Malaysia Kesebelas (Eleventh Malaysia Plan) : 2016-2020*. 2015;1–372.
20. Cossent, R. Gómez, T and Frías, P. Towards a future with large penetration of distributed generation: Is the current regulation of electricity distribution ready? Regulatory recommendations under a European perspective. *Energy Policy*. 2009;37(3):1145–55.
21. Chiradeja, P and Ramakumar, R. Voltage profile improvement with distributed wind turbine generation-a case study. In: 2003 IEEE Power Engineering Society General Meeting (IEEE Cat No03CH37491). IEEE; p. 2331–6.

22. Thacker, T. Boroyevich, D. Burgos, R and Wang, F. Phase-Locked Loop Noise Reduction via Phase Detector Implementation for Single-Phase Systems. *IEEE Transactions on Industrial Electronics*. 2011;58(6):2482–90.

23. Jiayi, H. Chuanwen, J and Rong, X. A review on distributed energy resources and MicroGrid. Vol. 12, Renewable and Sustainable Energy Reviews. 2008. p. 2465–76. (editor & translator; vol. 12).

24. Kyriakarakos, G. Dounis, AI. Rozakis, S. Arvanitis, KG and Papadakis, G. Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel. *Applied Energy*. 2011;88(12):4517–26.

25. Katiraei, F and Iravani, MR. Power Management Strategies for a Microgrid With Multiple Distributed Generation Units. *IEEE Transactions on Power Systems*. 2006;21(4):1821–31.

26. Amjady, N. Keynia, F and Zareipour, H. Short-term load forecast of microgrids by a new bilevel prediction strategy. *IEEE Transactions on Smart Grid*. 2010;1(3):286–94.

27. Ardeshna, NK and Chowdhury, BH. Supporting islanded microgrid operations in the presence of intermittent wind generation. In: IEEE PES General Meeting. IEEE; 2010. p. 1–8.

28. Schillings, C. Pereira, EB. Perez, R. Meyer, R. Trieb, F and Renné, D. HIGH RESOLUTION SOLAR ENERGY RESOURCE ASSESSMENT WITHIN THE UNEP-PROJECT SWERA. World Renewable Energy Congress VII. 2002. p. 6.

29. Sadrul Islam, AKM. Rahman, MM. Mondal, MAH and Alam, F. Hybrid energy system for St. Martin island, Bangladesh: An optimized model. In: Procedia Engineering. 2012. p. 179–88. (editor & translator; vol. 49).

30. Surprenant, M. Hiskens, I and Venkataramanan, G. Phase locked loop control of inverters in a microgrid. *2011 IEEE Energy Conversion Congress and Exposition*. 2011;667–72.

31. Karimi-Ghartemani, M and Iravani, MR. A Method for Synchronization of Power Electronic Converters in Polluted and Variable-Frequency Environments. *IEEE Transactions on Power Systems*. 2004;19(3):1263–70.

32. Lentijo, K and Opila, DF. Minimizing inverter self-synchronization due to reactive power injection on weak grids. *2015 IEEE Energy Conversion*

Congress and Exposition, ECCE 2015. 2015;1136–42.

33. Patino, DG. Erira, EGG. Rosero, EE and Fuelagan, JR. SOGI-FLL for synchronization and fault detection in an inverter connected to the grid. In: 2015 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT LATAM). IEEE; 2015. p. 833–8.
34. Freijedo, FD. Doval-Gandoy, J. Lopez, O. Martinez-Penalver, C. Yepes, AG. Fernandez-Comesana, P. Malvar, J. Nogueiras, A. Marcos, J and Lago, A. Grid-synchronization methods for power converters. *Industrial Electronics 2009 IECON 09 35th Annual Conference of IEEE*. 2009;522–9.
35. Bojoi, RI. Griva, G. Bostan, V. Guerriero, M. Farina, F and Profumo, F. Current Control Strategy for Power Conditioners Using Sinusoidal Signal Integrators in Synchronous Reference Frame. *IEEE Transactions on Power Electronics*. 2005;20(6):1402–12.
36. Barbosa Rolim, LG. Rodrigues da CostaJr., D and Aredes, M. Analysis and Software Implementation of a Robust Synchronizing PLL Circuit Based on the pq Theory. *IEEE Transactions on Industrial Electronics*. 2006;53(6):1919–26.
37. Panda, SR and Babu, BC. Phase estimation for grid synchronization using CORDIC algorithm with SRF-PLL. In: 2012 IEEE Students' Conference on Electrical, Electronics and Computer Science. IEEE; 2012. p. 1–4.
38. Yang, Y. Wang, H and Blaabjerg, F. Reactive Power Injection Strategies for Single-Phase Photovoltaic Systems Considering Grid Requirements. *IEEE Transactions on Industry Applications*. 2014;50(6):4065–76.
39. Zhang, L. Sun, K. Hu, H and Xing, Y. A System-Level Control Strategy of Photovoltaic Grid-Tied Generation Systems for European Efficiency Enhancement. *IEEE Transactions on Power Electronics*. 2014;29(7):3445–53.
40. Han, Y. Shen, P and Guerrero, JM. Stationary Frame Current Control Evaluations for Three-Phase Grid-Connected Inverters with PVR-based Active Damped LCL Filters. *Journal of Power Electronics*. 2016;16(1):297–309.
41. Carugati, I. Donato, P. Maestri, S. Carrica, D and Benedetti, M. Frequency adaptive PLL for polluted single-phase grids. *IEEE Transactions on Power Electronics*. 2012;27(5):2396–404.
42. IEEE. IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems. *Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage Published*.

2003;2014(July):1–28.

43. Rodríguez, P. Luna, A. Ciobotaru, M. Teodorescu, R and Blaabjerg, F. Advanced grid synchronization system for power converters under unbalanced and distorted operating conditions. In: IECON Proceedings (Industrial Electronics Conference). 2006. p. 5173–8.
44. Patiño, DG. Erira, EGG. Rosero, EE and Fuelagán, JR. SOGI-FLL for synchronization and fault detection in an inverter connected to the grid. *2015 IEEE PES Innovative Smart Grid Technologies Latin America, ISGT LATAM 2015*. 2016;833–8.
45. Tolani, S. Sasmal, TS and Sensarma, P. Low-cost digital realization of phase synchronization for grid tied micro inverter. In: 2015 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE; 2015. p. 5991–7.
46. Newman, MJ and Holmes, DG. Delta operator digital filters for high performance inverter applications. *IEEE Transactions on Power Electronics*. 2003;18(1):447–54.
47. Ciobotaru, M. Teodorescu, R and Blaabjerg, F. A New Single-Phase PLL Structure Based on Second Order Generalized Integrator. In: 37th IEEE Power Electronics Specialists Conference. IEEE; p. 1–6.
48. Karimi-Ghartemani, M. A novel three-phase magnitude-phase-locked loop system. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 2006;53(8):1792–802.
49. Karimi-Ghartemani, M. Karimi, H and Iravani, MR. A Magnitude/Phase-Locked Loop System Based on Estimation of Frequency and In-Phase/Quadrature-Phase Amplitudes. *IEEE Transactions on Industrial Electronics*. 2004;51(2):511–7.
50. Kothari, DP and Nagrath, IJ. Electric Machines. New Delhi: Tata McGraw Hill Publishing Company Limited; 2004.
51. J. Chapman, S. Electric Machinery Fundamentals. 4th ed. McGraq Hill; 2005. 267-345 p.
52. Grainer, JJ and Stevenson, W. Power System Analysis [Internet]. Vasa. 1994. 787 p.
53. shahariari, A. Mokhlies, H. Bin Abu Bakar, AH and Karimi, M. The numerical estimation method of series FACTS compensator based on injection model of voltage source inverter. In: 2011 IEEE Symposium on Industrial Electronics

and Applications. IEEE; 2011. p. 490–4.

54. Mohr, M and Fuchs, FW. Comparison of Three Phase Current Source Inverters and Voltage Source Inverters Linked with DC to DC Boost Converters for Fuel Cell Generation Systems. *European Conference on Power Electronics and Applications*. 2005;10.

55. Teodorescu, R. Blaabjerg, F. Borup, U and Liserre, M. A new control structure for grid-connected LCL PV inverters with zero steady-state error and selective harmonic compensation. In: Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition, 2004 APEC '04. IEEE; p. 580–6. (editor & translator; vol. 1).

56. Mummadi, V. Design of Robust Digital PID Controller for H-Bridge Soft-Switching Boost Converter. *IEEE Transactions on Industrial Electronics*. 2011;58(7):2883–97.

57. Rolim, LGB. Da Costa, DR and Aredes, M. Analysis and software implementation of a robust synchronizing PLL circuit based on the pq theory. *IEEE Transactions on Industrial Electronics*. 2006;53(6):1919–26.

58. Nise, NS. Control Systems Engineering. Sixth Edit. John Wiley & Sons, Inc.; 2006.

59. Paul M, Anderson A. A., F. Power System Control and Stability. 2nd ed. USA: Willey-IEEE Press;

60. Kawai, M. Sakai, Y. Sugiyama, H and Taoka, H. Frequency improvement in power system by Synchronization Inverter-based distributed generators. *Proceedings - 2015 International Symposium on Smart Electric Distribution Systems and Technologies, EDST 2015*. 2015;93–8.

61. Sovacool, BK and Drupady, IM. Examining the small renewable energy power (SREP) program in Malaysia. *Energy Policy*. 2011;39(11):7244–56.

62. Transformers, D. IEEE Standard Terminology for Power and Distribution Transformers. *Std C571280^{TM}-2002*. 2002;2002(November):0_1-.